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ORIGINAL ARTICLE

Determining Optimum Pumping Rates of Groundwater in Ttansum Island Related to Riverbank Filtration

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Abstract

Riverbank Filtration (RBF) is a kind of indirect artificial recharge method and is useful in obtaining higher-quality source water than surface water when procuring municipal water. This study evaluated optimal riverbank filtered water and the productivity of the radial collector wells on Ttansum Island in the area downstream of the Nakdong River, where Gimhae City is constructing a municipal water plant for the purpose of acquiring high-quality water. The RBF wells are planned to provide water to the citizens of Gimhae City through municipal water works. Groundwater flow modeling was performed with the following four scenarios: (a) 9 radial collector wells, (b) 10 radial collector wells, (c) 10 radial collector wells and two additional vertical wells, and (d) 12 radial collector wells. This study can be useful in determineing the optimum production rate of bank filtrated water not only in this study area but also in other places in Korea.

Key words : Optimum pumping rate, Riverbank filtration, Ground water modeling, Ttansum Island, Radial collector well

1. Introduction

Riverbank Filtration (RBF) is a kind of indirect artificial recharge method, which involves installing wells in riverside alluvium for intaking water originating from rivers. In this case, the determining optimal pumping rate in relation to an appropriate groundwater level, as well as the seasonal variation of river discharges, is critical. The RBF has some advantages compared to direct surface water intake, such as higher potable water quality than natural surface water due to the natural purification of alluvial deposits (Hiscock and Grischek, 2002). European countries like Germany, the Netherlands, France, Austria, and Sweden have procured drinking water by means of the RBF method since the 19th century. Germany procures 15~16 % of its total drinking water using RBF (Achten et al., 2002). In the United States, the RBF method for drinking water production has been implemented in Columbia, Missouri, Mississippi, Ohio, Colorado, Rio Grande, Russian, and Connecticut river basins (Ray, 2001).

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Numerical modeling has been implemented to predict changes in groundwater levels, groundwater flow, aquifer storage, as well as groundwater budget and the recharge rate for groundwater management, as shown in Selroos et al.(2002), Senthilkumar and Elango(2004), Polomčić et al.(2013), and Song et al.(2015). Polomčić et al.(2013) carried out numerical modeling for considering the infiltration channel at the Vić Bare RBF site in Serbia. Shankar et al.(2009) reported the result of the numerical modeling of RBF for groundwater-surface water ratio estimation at Grind well field near Düsseldorf, Germany. Elsawwaf et al.(2012) revealed groundwater heads and groundwater flows in Lake Nasser, Egypt, using the analytical solution of Edelman(1947).

Numerous hydrogeological studies like Cheong et al.(2003), Hamm et al.(2002), and Hyun et al.(2006) were conducted in the Changwon RBF area. Several studies on the hilseo RBF area were carried out by using hydrochemical approaches (Kim et al., 2003) and hydrogeological methods (Hamm et al., 2003). A hydrochemical study of the Goryeong RBF area was carried out by Kim et al.(2003). Hamm et al.(2004) revealed the hydrogeological characteristics of the Nakdong River and the riverside fluvial aquifers at the Book-myeon RBF site, Changwon City, using groundwater flow modeling. Hamm et al.(2005) estimated the groundwater flow and the amount in the Changwon area of RBF for public water supply. Won et al.(2006) analyzed seasonal groundwater level fluctuations in alluvial aquifers and the recharge of river water into the aquifers in the Nakdong River, Goryong-gun, Gyeongbuk province, using a 2-D groundwater flow modeling. Chung et al.(2011) estimated the daily groundwater recharge rates in the Jincheon area using an integrated SWAT-MODFLOW model.

This study aims to evaluate the optimal riverbank filtered water and the productivity of the radial collector wells on the Ttansum Island in the Masari area, located at the junction of the Nakdong River and its tributary Miryang River, using groundwater flow modeling. A riverside filtered water plant is planned to provide drinking water to the citizens of Gimhae City through municipal water works.

2. Materials and methods

2.1. Study area

On the Ttansum Island in the Masari area, RBF wells are constructed for the purpose of providing municipal water plant to the citizens of Gimhae City (Fig. 1). Ttansum Island covers an area of ~0.7 km^2, having a spindle shape with the length of the major axis being ~1.4 km and that of the minor axis being ~800 m. It is a river island located at the junction of the Nakdong River and its tributary, Miryang River. The majority of the water on the western side of Ttansum Island flows from southwest to northeast, while a minor part of the water flows between the eastern side of Ttansum Island and the Nakdong River. The Miryang River that flows from the north side of Ttansum Island to the south, eventually joining, the Nakdong River. In the past, the Ttansum Island was used for greenhouse farming. The island has changed because of riverbank filtration, channel reconstruction, and dredging on the left side of the island to the Nakdong River in 2010 by the Gimhae City, resulting in the reduction of Ttansum's area from 1.02 km^2 to 0.7 km^2 (Kim et al., 2012).

According to the data from Water Resources Management Information System (WAMIS) for 2008 to 2012 at the Gimhae weather station, which is the closest to the study area, the average annual precipitation of the study area is 1,309 mm, with the highest being in 2011 (1,481 mm) and the lowest being in 2008 (967 mm). The average monthly rainfall from 1982 to 2012 was 16.6 mm in January, 51.8 mm in February, 71.8 mm in March, 115.6 mm in April, 161.4 mm in June, 358.6 mm in July, 154.2

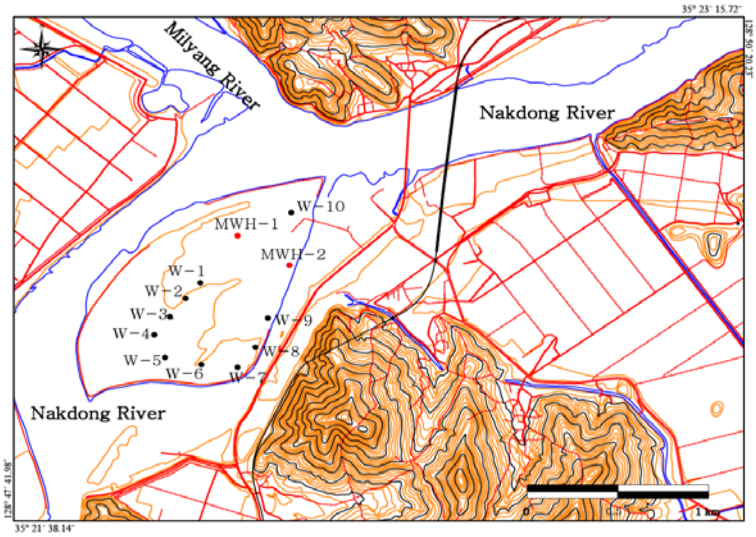


Fig. 1. Location of study area and wells.

mm in August, 131.0 mm in September, 51.4 mm in October, 46.8 mm in November and 25.6 mm in December, with the highest precipitation (358.6 mm) being in July and the lowest precipitation (16.6 mm) being in January.

The average annual temperature of the area is 15.4℃ based on the WAMIS data from 2008 to 2012 at the Gimhae weather station. The lowest and highest average monthly temperatures for the period from 2008 to 2012 are 0.9℃ in January and 27.5℃ in August, respectively. On the other hand, the average monthly sunshine hours from 2008 to 2012 showed the longest and shortest daylight hours of 7.3 hours and 5.1 hours in April and July, respectively. The average annual maximum sunshine hours were the highest (6.8 hours) in 2012 and the lowest (6.0 hours) in 2011.

In the study area, 10 radial collector wells, as well as 2 vertical wells, have been installed for providing RBF source water to the municipal water works for supplying to Gimhae City. From a total of 33 boreholes that were drilled for a detailed investigation between 2010 and 2013 (Fig. 2), the site geology was revealed as sand layer, clayey sand layer, silt clay layer, sand layer, sand/gravel layer, and weathered rock in descending order from the land surface (Table 1). The sand layer that is distributed between 10.3 and 23.0 m below the surface has a dark brown to light gray color and very loosely arranged to medium density. The clayey sand layer that is distributed between 16.0 and 29.7 m below the surface mainly shows dark gray color and low to medium density, with a small part consisting of shells. The silty clay layer that is distributed 20.0 - 29.0 m below the surface has a dark gray color similar to that of the clayey sand layer and shows very low to medium density. The lower sand layer has a light brown to light gray color as well as low to medium density. The sand/gravel layer is distributed between 25.0 and 43.3 m below the surface, and has a light gray to grayey brown color, as well as high to very high density. The gravel sizes range from 0.5 to 13.0 cm, with an average of 6.2 cm (Daewoo E & C, 2013).

Groundwater levels from Dec 7, 2012 to Dec 31, 2012, measured in the ten monitoring wells (W-1 to W-10), showed a mean groundwater level of -11.81

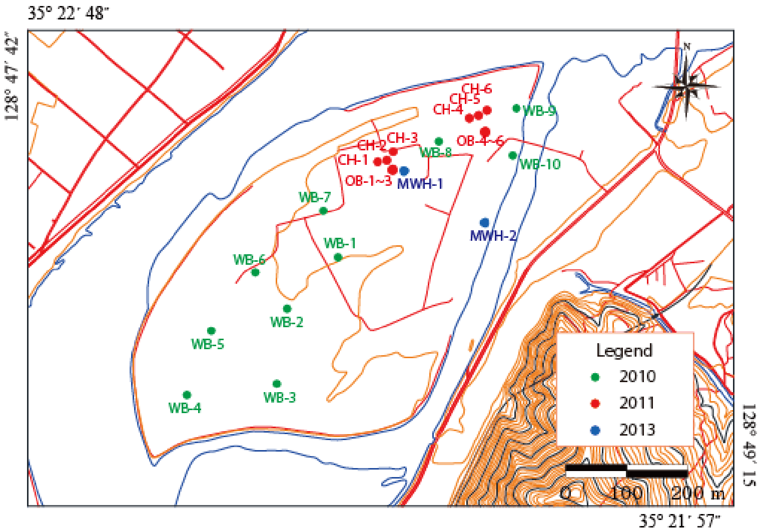


Fig. 2. Installed wells in the years of 2010, 2011, and 2013.

Table 1. Geological properties of boreholes (Daewoo E & C, 2013)

Well No.	Sand	Clayey sand	Silt/ clay	Sand	Sand/ gravel	Weathered zone	Total depth
WB-1	15.5	22.0	24.0	29.0	41.8	44.0	44.0
WB-2	17.0	23.0	25.0	29.0	41.0	43.0	43.0
WB-3	15.0	25.0	28.0	31.0	39.5	42.0	42.0
WB-4	-	21.0	29.0	30.0	42.5	44.0	44.0
WB-5	23.0	26.0	-	-	41.2	42.0	42.0
WB-6	18.0	20.0	26.0	27.5	41.3	43.0	43.0
WB-7	13.0	16.0	26.0	27.5	39.5	41.0	41.0
WB-8	13.0	24.0	24.0	28.0	43.3	44.0	44.0
WB-9	11.0	16.0	23.0	28.0	38.5	40.0	40.0
WB-10	14.0	19.0	23.0	28.0	43.0	45.0	45.0
OB-1	14.5	-	25.0	28.9	37.0	-	37.0
OB-2	14.5	-	24.5	26.0	-	-	26.0
OB-3	14.6	-	24.6	26.0	-	-	26.0
OB-4	10.8	24.0	-	27.7	30.0	-	30.0
OB-5	10.8	17.0	23.5	28.8	39.0	-	39.0
OB-6	10.3	21.0	23.5	26.0	-	-	26.0
CH-1	13.0	-	24.0	26.0	27.0	-	27.0
CH-2	13.0	-	24.0	25.0	26.0	-	26.0
CH-3	11.8	-	25.0	-	26.0	-	26.0
CH-4	12.0	-	22.0	25.0	26.0	-	26.0
CH-5	14.0	19.0	-	22.0	25.0	-	25.0
CH-6	12.0	17.0	20.0	24.0	25.0	-	25.0
MWH-1	14.7	20.5	25.5	26.9	36.7	37.0	37.0
MWH-2	19.0	29.7	-	-	40.7	41.0	41.0
Min.	10.3	16.0	20.0	22.0	25.0	37.0	25.0
Max.	23.0	29.7	29.0	31.0	43.3	45.0	45.0
Median	14.0	21.0	24.3	27.5	39.0	42.5	38.0
Mean	14.1	21.2	24.5	27.2	35.7	42.2	35.2

Table 2. Groundwater level of observation wells (unit: meter, amsl)

	7 Dec. 2012 – 31 Dec. 2012			1 Jan. 2013 – 4 Jun. 2013		
Well no.	Mean	Min.	Max.	Mean	Min.	Max.
W-1	-12.45	-13.01	-11.72	-12.66	-13.50	-11.47
W-2	-12.76	-13.02	-12.49	-12.60	-13.10	-12.22
W-3	-11.60	-12.10	-10.95	-11.95	-12.86	-10.17
W-4	-10.92	-11.45	-10.23	-11.34	-12.26	-9.85
W-5	-12.33	-13.22	-10.45	-12.88	-13.42	-10.64
W-6	-12.91	-13.18	-12.54	-12.89	-13.42	-12.52
W-7	-12.93	-13.20	-12.74	-10.38	-13.60	-
W-8	-12.89	-13.30	-12.70	-10.39	-13.40	-
W-9	-12.55	-13.18	-10.25	-12.89	-13.35	-12.38
W-10	-6.75	-7.20	-4.32	-7.39	-10.00	-6.69

m (above mean sea level, amsl), with the highest and lowest groundwater levels being -4.32 m (amsl) and -13.30 m (amsl), respectively (Table 2). On the other hand, groundwater levels from Jan 1, 2013 to Jun 4, 2013 displayed mean groundwater level of 11.54 m (amsl) with the highest and lowest groundwater levels of -6.69 m (amsl) and -13.60 m (amsl), respectively. The groundwater levels from Jan. 1, 2013 until Jun. 4, 2013 were used for the calibration of the transient modeling considering the operation of the radial collector wells on Ttansum Island.

2.2. Experimental methods

The pumping test for estimating the hydraulic parameters of aquifers measures changes in water levels until a certain peried of pumping with a constant amount of pumping. Time-water level change is applied to estimate the hydraulic parameters using equations like Theis (1935), Papadopulo-Cooper (1967), Hantush (1960, 1962), Hantush-Jacob (1955), Moench (1985), and Neuman-Witherspoon (1969), depending on the type of aquifer. The strata in this study area consist of sand layer, sand layer including silt, clay layer, coarse sand layer, sand gravel layer, and weathered zone from shallow to deeper parts. Based on the hydrogeological units, a pumping test analysis was performed using the Neuman-Witherspoon (1969) equation.

Groundwater modeling can assess and predict quantitative changes in groundwater levels, groundwater flow, aquifer storage change, groundwater balance, and groundwater recharge rates by simplifying complex groundwater systems. Groundwater modeling is executed by inserting climate data, borehole strata, groundwater data, and hydraulic parameters (hydraulic conductivity, transmissivity) in pumping water tests. Steady state simulation was conducted for determining the natural groundwater level prior to the installation of the wells, while transient simulation was carried out during the operation of radial collector wells and one vertical well (Neuman-Witherspoon, 1969; Hantush-Jacob, 1955; Moench, 1985). In this study, groundwater modeling was performed using Schlumberger's Visual MODFLOW (ver. 2011.1), which is a 3-D groundwater flow modeling software using the finite difference method. MODFLOW (McDonald, and Harbaugh, 1988) is included in Visual MODFLOW (ver. 2011.1).

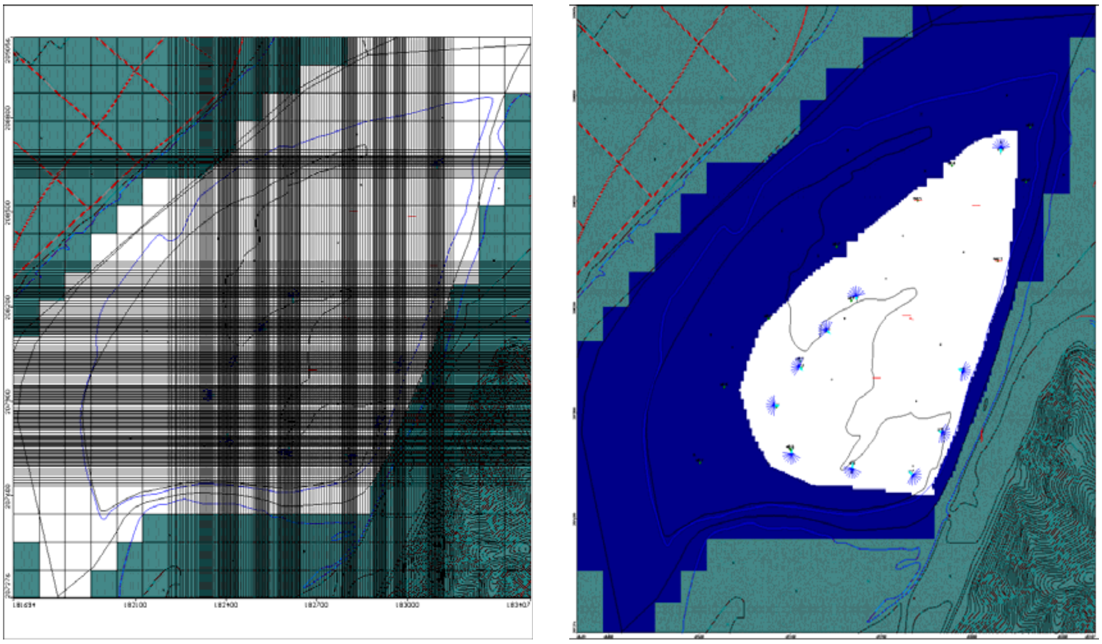
3. Results

3.1. Construction of the groundwater model

Ttansum Island, which belongs to Gimhae City in Gyeongsangnam-do province and has nearly no relief bounded by the Nakdong River, was decided as the model domain based on digital topographic map (1: 25,000). Ttansum Island is surrounded by the Nakdong River that is fixed as the river boundary (blue part in Fig. 3). The cells in the outer par of the model domain are considered inactive. The total number of cells are 42,315 (i.e. =195 × 217), with narrower spaces in the vicinity of the radial collector wells and wider spaces in other parts of the area (Table 3). The alluvial deposit consists of six layers (fine sand layer, sand layer containing clay, clay layer, coarse sand layer, sand/gravel layer, and weathered zone) based on Daewoo E & C's design report (2006), as well as the data from 2010-2013 (Fig. 4).

The width of the Nakdong River was estimated based on the RBF design report of Gimhae City (Daewoo E & C, 2006). The mean water-level data of the Nakdong River from 2012, collected at the Samrangjin station was obtained from WAMIS (http://www.wamis.go.kr/eng/main.aspx).

Based on the data of Daewoo E & C's design report (2006), the hydraulic conductivity (K) values



(a) (b)

Fig. 3. Model grids (a) and model boundaries (b).

Table 3. Grid spacing and number of grids in model domain

Grid spacing (m)	2-80
Column numbers	217
Row numbers	195
Numbers of layers	6

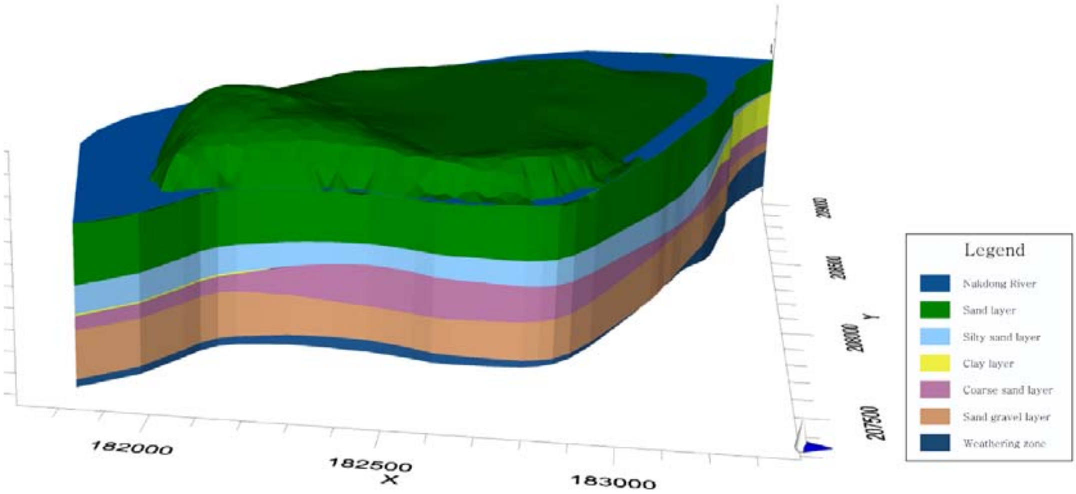


Fig. 4. Layers of the model domain.

Table 4. Initial horizontal hydraulic conductivity (*K*) values for the layers

Layer	Zone	Horizontal *K* (m/s)
1	Fine sand	7.25×10^{-5}
2	Clayey sand	1.80×10^{-5}
3	Silt clay	4.34×10^{-6}
4	Coarse sand	1.43×10^{-4}
5	Sand/gravel	2.48×10^{-4}
6	Weathered	4.43×10^{-5}

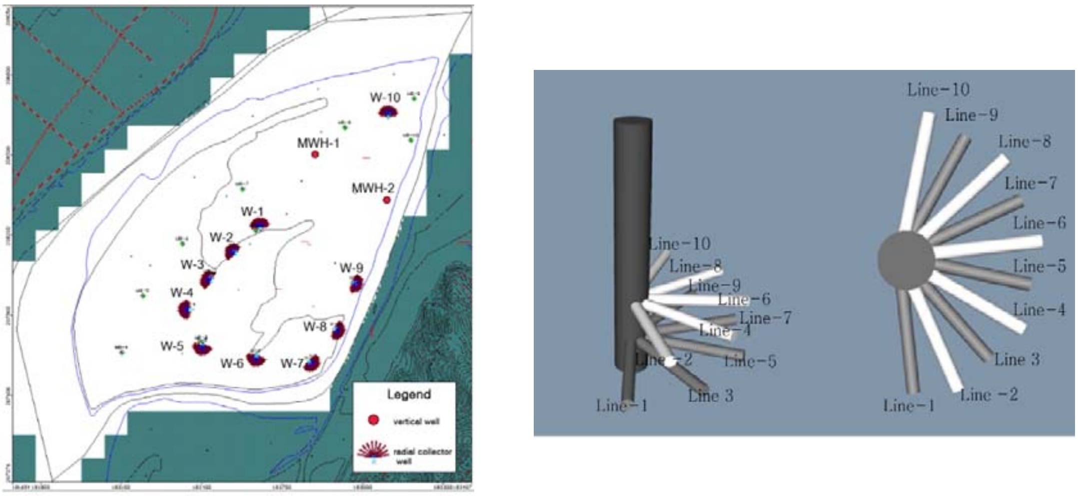
of the alluvial deposit are assined the highest value of 2.48×10^{-4} m/s (sand/gravel layer) and the lowest value of 4.34×10^{-6} m/s (clay layer) in Table 4. The K value (4.85×10^{-4} m/s) of the Nakdong River was obtained from the Korea Institute of Civil Engineering and Building Technology (2005).

A specific storage (S_s) of 9.16×10^{-6} m^{-1} for the main aquifer, i.e. the sand/gravel layer, was inserted into the model from the result of the pumping test conducted at PW-2 (Pusan National University, 2011). The S_s value for the other layers was assigned as 9.16×10^{-7} m^{-1}, while specific yield (S_y) values of 0.3 and 0.2 were assigned for the sand/gravel layer and the other layers, respectively (Table 5). Effective porosity (n_e) values of 0.2 and 0.15 were assigned for the sand gravel layer and for the other layers, respectively (Table 5).

According to Daewoo E & C (2006), the 5 upper horizontal arms and 5 lower horizontal arms are arranged so as to be staggered at intervals of 1 m in

Table 5. Hydraulic parameters for the layers

Layer	S_s (m^{-1})	S_y	Effective porosity(n_e)	Porosity (n)
All Except sand/gravel	9.16×10^{-7}	0.2	0.15	0.2
Sand/gravel	9.16×10^{-6}	0.3	0.2	0.3



(a) (b)

Fig. 5. (a) Radial collector and vertical wells in modeling and (b) diagram for horizontal arms of radial collector well.

the sand/gravel layer. The horizontal arms of the radial collector wells, which have a length of 30 m and a diameter of 20 cm, are divided into 8 grids that correspond to 30 m (=3.75m × 8 grids). For the modeling, the W-1 to W-4 and W-10 radial collector wells were arranged to the west, the W-5 and W-6 wells were arranged southward and the W-7 to W-9 wells were arranged eastward (Fig. 5(a)). The arms displayed a fan shape with an angle of 150° between the two adjacent arms. Each radial collector well contained 10 horizontal arms that had 8 fine cells. The 10 horizontal arms were numbered from Line 1 to Line 10 in the clockwise direction (Fig. 5(b)). The diameter of the horizontal arms was simulated by a fine cell corresponding to the screen zone (0.2 m). Consequently, the pumping rate from each fine cell (129 m^3/day) corresponds to the pumping rate (1,032 m^3/day), which is 1/8 of one arm's pumping rate of the collector well (Fig. 6).

3.2. Steady-state simulation result

Steady-state modeling was performed for determining the natural-state of groundwater distribution before the installation of the radial collector wells. Model

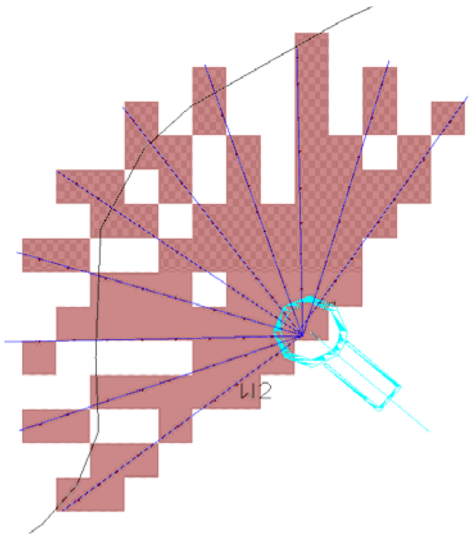


Fig. 6. Horizontal arms of the W-2 well.

calibration was conducted for comparing the calculated groundwater levels to the observed groundwater levels at the 4 monitoring wells (WB-1, WB-10, PB-1 and PB-2) by changing boundary conditions, hydraulic conductivity values, and groundwater recharge rates, based onthe data from Daewoo E & C (2006) and Intellegeo (2010). By

Table 6. Hydraulic conductivity (*K*) values by the model calibration

Layer	Horizontal *K* (m/sec)	Vertical *K* (m/sec)
Fine sand	7.25×10^{-5}	7.25×10^{-6}
Clayey sand	1.80×10^{-5}	1.80×10^{-6}
Silt clay	4.37×10^{-6}	4.37×10^{-7}
Coarse sand	1.43×10^{-4}	1.43×10^{-5}
Sand/gravel	3.02×10^{-3}	3.02×10^{-4}
Weathered	4.43×10^{-5}	4.43×10^{-6}

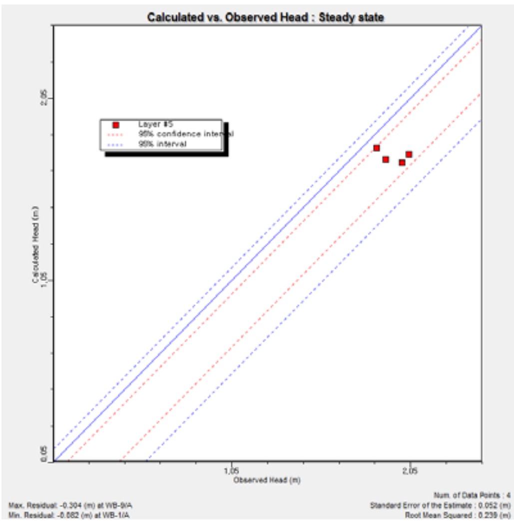
calibration, the horizontal K values of the fine sand layer, the sand layer containing clay, the clay layer, the coarse sand layer, the sand/gravel layer, and the weathered zone were determined to be 7.25×10^{-5}, 1.80×10^{-5}, 4.37×10^{-6}, 1.43×10^{-4}, 3.02×10^{-3}, and 4.43×10^{-5} m/sec, respectively (Tables 6).

A confidence interval of 95% was obtained between the calculated groundwater level and observed groundwater level by model calibration, which indicates that the object aquifer system was simulated fairly well. Groundwater level contours by the steady state simulation showed higher oval distribution in the central part of the Ttansum Island (Fig. 7).

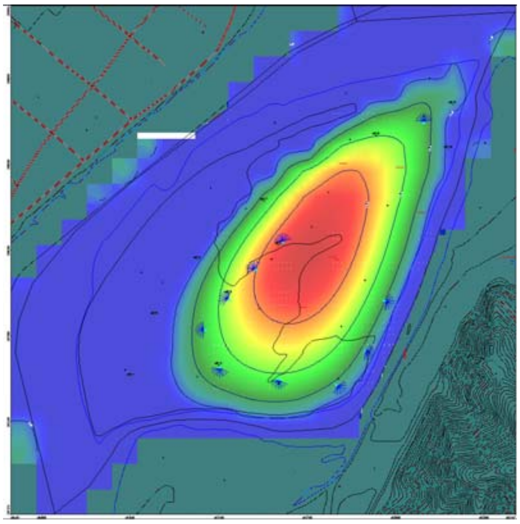
3.3. Determination of the optimal pumping rates

The transient flow modeling estimated the optimal pumping rate with the designed stable water level of -11.55 m (amsl) for the four scenarios of (1) the 9 radial collector wells (W-1 ~ W-9), (2) the 10 radial collector wells (W-1 ~ W-10), (3) the 10 radial collector wells and two vertical wells (MWH-1, MWH-2), and (4) the 12 radial collector wells (W-1 ~ W-12).

As a result of the 1-year transient simulation on the 9 radial collector wells (W-1 ~ W-9), the optimum pumping amount was estimated to be 102,325 m^3/day in agreement with the designed stable level (Table 7, Fig. 8). For the 1-year transient simulation using 10



(a)



(b)

Fig. 7. (a) Results of steady-state model calibration and (b) groundwater level distribution.

Table 7. Result of the transient modeling of scenario 1 using 9 wells (W-1 ~ W-9)

Well	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8	W-9	Total pumping amount	Mean water level
Pumping rate (m^3/d)	18,878	9,780	18,878	19,105	11,145	9,325	2,047	3,639	9,553	102,325	-
Stable water level (m, amsl)	-11.57	-11.28	-10.85	-10.48	-11.97	-11.98	-11.77	-11.96	-12.10	-	-12.31

Table 8. Pumping rate and stable water level of the 10 radial collector wells (Daewoo E & C, 2013)

Well	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8	W-9	W-10	Pumping amount	Mean water level
Pumping rate (m^3/d)	19,920	10,320	19,920	20,160	3,840	11,760	9,840	2,160	10,080	-	108,000	-
Water level (amsl)	-12.22	-12.50	-11.41	-10.72	-12.84	-12.75	-12.85	-12.75	-12.75	-	-	-12.31

radial collector wells (W-1 ~ W-10), the pumping rate of the W-1 to W-9 wells was obtained from the test pumping on May 3, 2013 (Table 8) and the W-10 well data was referred to the test pumping on June 3, 2003. The pumping amount of each radial collector well was estimated considering the ratio of the total

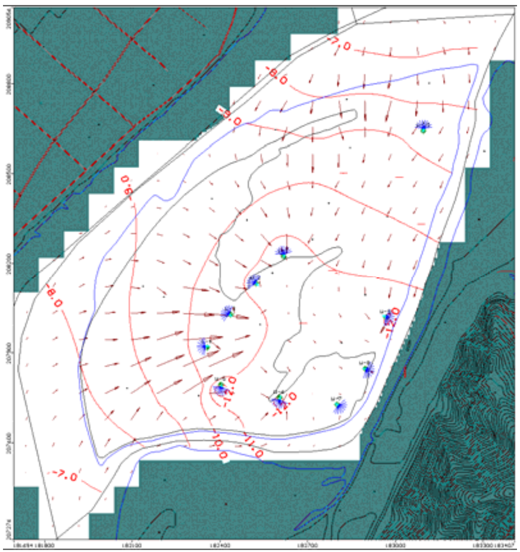


Fig. 8. Groundwater level distribution of nine radial collector wells (W-1 ~ W-9) for the designed stable level.

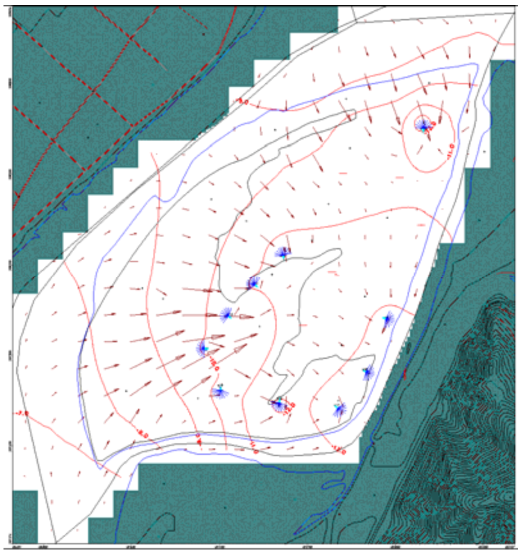


Fig. 9. Groundwater level distribution of ten radial collector wells (W-1 ~ W-10) for the designed stable level.

Table 9. Result of the transient modeling of scenario 2 using ten wells (W-1 ~ W-10)

Well	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8	W-9	W-10	Pumping amount	Mean water level
Pumping rate (m^3/d)	16,709	8,656	16,709	16,910	3,221	9,864	8,254	1,812	8,455	16,910	107,500	-
Stable water level (m, amsl)	-11.56	-11.09	-10.51	-10.06	-10.47	-12.06	-12.55	-12.23	-12.44	-12.03	-	-11.50

amount to the amount at each radial collector well. According to the simulated groundwater level distribution, the groundwater flow converges to the direction of the W-1 to W-5 wells and a slight decline in groundwater level occurs in the vicinity of the W-10 well (Table 9, Fig. 9). The optimum amount was determined to be 107,500 m^3/day with the mean groundwater level of -11.50 m (amsl) being nearly the same as the designed stable level.

For the transient simulation using the 10 radial collector wells and the two vertical wells, the vertical wells (MWH-1 and MWH-2) were specified by the data from Daewoo E & C (2013) and a pumping rate of 2,500 m^3/day. The pumping rate was corrected by changing the ratio of the total amount of water pumped to the pumping amount at each well. The 1-year transient simulation resulted in an optimal pumping amount fo 110,000 m^3/day, with amean groundwater level of －11.84 m (amsl), which is slightly larger than the designed stable level (Table 10, Fig. 10).

The transient simulation using the 12 radial

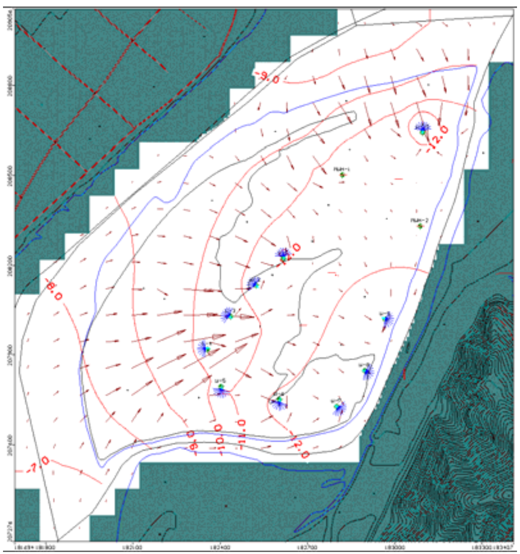


Fig. 10. Groundwater level distribution of ten radial collector wells (W-1 ~ W-10) and two vertical wells (MWH-1 and MWH-2) for the designed stable level.

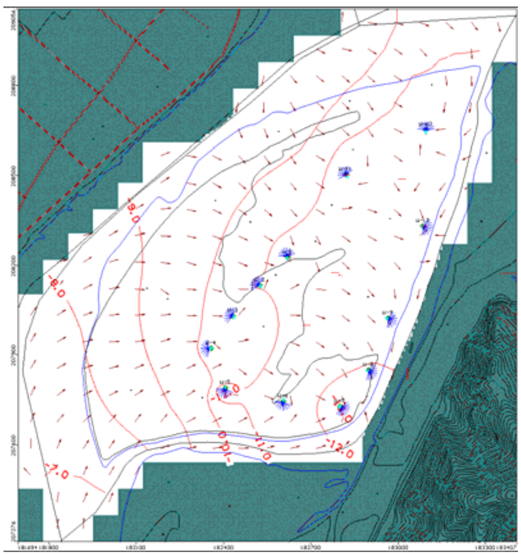


Fig. 11. Groundwater level distribution of ten radial collector wells (W-1 ~ W-12) for the designed stable level.

Table 10. Result of the transient modeling of scenario 3 using the 10 wells (W-1 ~ W-10) and 2 vertical wells (MWH-1 and MWH-2)

Well	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8	W-9	W-10	MWH-1	MWH-2	Pumping amount	Mean water level
Pumping rate (m^3/d)	16,455	8,525	16,455	16,654	3,172	9,715	8,129	1,784	8,327	16,654	2,065	2,065	110,000	-
Stable water level (m, amsl)	-11.96	-11.42	-10.81	-10.33	-10.74	-12.37	-12.90	-12.62	-12.91	-12.58	-11.54	-11.95	-	-11.84

Table 11. Result of the transient modeling of scenario 4 using the 12 wells (W-1 ~ W-12)

Well	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8	W-9	W-10	W-11	W-12	Pumping amount	Mean water level
Pumping rate (m^3/d)	13,417	6,951	14,500	18,000	9,000	7,000	14,500	1,500	3,000	13,578	5,000	5,000	111,445	-
Stable water level (m, amsl)	-11.54	-11.05	-10.61	-10.28	-11.63	-11.86	-12.84	-12.09	-11.87	-11.56	-11.70	-11.74	-	-11.56

Table 12. Evaluation of optimum pumping rate according to transient modeling conditions

Transient modeling conditions	Pumping rate (m^3/day)	Calculated mean water level (m, amsl)	Stable water level (Safety rate 10%) (m, amsl)
Scenario 1	102,325	-11.55	-11.55 (-12.71)
Scenario 2	107,500	-11.50	
Scenario 3	110,000	-11.84	
Scenario 4	111,445	-11.56	

collector wells (W-1 ~ W-12) resulted in an optimal pumping amount of 111,445 m^3/day, with a mean groundwater level of －11.56 m (amsl) (Table 11, Fig. 11). For this transient simulation, the locations of W-11 and W-12 wells were set to the locations of the vertical wells (MWH-1 and, MWH-2), respectively. Table 12 shows the optimum discharge from the pumping wells using the four scenarios on the Ttansum Island.

4. Conclusions

This study evaluated the optimal pumping rate from the aquifer based on 365 days of transient modeling with a designed stable water level of -11.55 m, amsl. The transient simulation was executed by using the pumping data from 10 collector wells (W-1 ~ W-10) on May 3 and June 3, 2013 as well as each pumping amount (2,500 m^3/day) determined by the step-drawdown test on two vertical wells (MWH-1 and MWH-2) on March 24 and March 25. The simulated pumping rates at each well were adjusted by the ratio of each well's pumping rate to the total pumping amount.

In the case of the 9 radial collector wells (W-1 ~ W-9), the optimum pumping amount in agreement with the designed stable level was estimated to be 102,325 m^3/day. In the case of the 10 radial collector wells (W-1 ~ W-10), the optimum amount (107,500 m^3/day) was determined corresponding to a water level of -11.50 m (amsl) which is approximately the same as the designed stable level. In the case of the 10 radial collector wells and two vertical wells, the optimum pumping amount was determined to be 110,000 m^3/day, with a groundwater level of －11.84 m (amsl), which is slightly larger than the designed stable level. Lastly, In the case of the 12 radial collector wells, the optimum pumping rate was determined to be 111,445 m^3/day, with a groundwater level of －11.56 m (amsl).

The result of this study can contribute to obraining drinking water by RBF in Gimhae City, as well as be usefully applied to other RBF sites in South Korea.

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